ASSESSMENT OF VEHICLE RELATED PEDESTRIAN SAFETY

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ABSTRACT

Against the background of upcoming intelligent safety systems, which also will have an impact on passive safety in general and on pedestrian safety in particular, all relevant technical measures have to be quantified in a combined way in order to find most effective solutions.

The article deals with the introduction of an assessment procedure called "**Ve**hicle **R**elated **P**edestrian **S**afety - index" (VERPS-index). This test procedure is exemplarily applied to two very different cars. Furthermore, the effectiveness of the uplifting hood applied to the front of these two sample cars is quantified.

Our approach consists of four modules: accident analysis, numerical simulation of kinematic impact parameters, component tests, and quantification of pedestrian safety. Current European component tests use impact parameters which are set more or less independent of the vehicle shape [1]. We propose to use numerical simulations in order to generate vehicle shape dependent test parameters. A weighting procedure based on accident statistics is applied to evaluate the relevance of each tested point on the front of the vehicle regarding its actual impact probability in real life. Thus, the VERPS-index is able to solve many of the disadvantages of a conventional component test compared to a full-scale test.

Based on the VERPS-index we are able to show in detail how the pedestrian safety performance depends on the vehicle front shape and how it differs for adults and children. Technical measures like an uplifting hood can clearly improve the safety performance. However, their effectiveness strongly depends on the individual vehicle's front geometry and differs for adults and children.

INTRODUCTION

13.8 Million accidents occur every year on European roads. These include 38.000 killed and 1.7 Million injured people resulting in costs of around 160 Billion Euros. This corresponds to around 2 % of the European gross national product [2]. These numbers prompted the Commission of the European Community to proclaim the goal to halve the number of road accident victims until 2010 [2]. There are 5.941 pedestrians among the fatalities on European roads [3]. This translates in a death rate for the EU for 2002 of 15.7 killed pedestrians per 1 Million inhabitants. In Australia this figure is 12.3, in the USA 16.4 and in Japan 21.8. Within the EU (EU_{15}, 2002) the rate differs between 6.4 in Sweden and 32.3 in Portugal. In Poland there are 52 killed pedestrians per 1 Million inhabitants [3, 4]. The number of killed vulnerable road users may even be higher in countries with a beginning motorisation, e.g. China.

The high number of pedestrian accidents justifies more safety efforts worldwide. There are different possible starting points:

- avoidance of accidents by measures related to infrastructure, education etc.
- avoidance of accidents by vehicle related, active measures
- mitigation of the consequences of accidents by:
  - reduction of accident severity by braking, steering, etc.

- decrease of the risk inflicted by the pedestrian's first impact on the car by structural design or active elements
- decrease of the dangerousness of the secondary impact on the road

• optimisation of the post crash rescue system

In the following chapters, opportunities are analysed to assess the safety performance of a vehicle concerning a pedestrian impact.

TEST PHILOSOPHIES

There are two different test philosophies in vehicle safety (see Figure 1 and Figure 2). Both of them have specific advantages and disadvantages.

Full-Scale Tests

Figure 1. Typical full-scale test, conducted at the Technical University of Berlin.

In full-scale tests the whole accident event is quite realistically reproduced. In principle, only the human is replaced by an anthropomorphic test device. The required dummies are mechanically complex. Additionally, complex data acquisition is necessary. The preparation of each individual experiment is time consuming. The reproducibility of full-scale-tests of pedestrian-car-crashes is not guaranteed. If conventional, not purpose designed dummies are used, biofidelity is questionable [5, 6]. The WAD (Wrap Around Distance) can not be reliably reproduced compared to PMHS-tests (Post Mortem Human Subject). Possibly the use of the newly developed POLAR II-Dummy can solve these problems and lead to a different perspective of the full-scale test in the field of pedestrian safety [7].

In principle, numerical simulation has the potential of a comprehensive assessment. Today, vehicle engineers routinely generate detailed numerical vehicle models which can be used to support such a process. But available numerical pedestrian models are not detailed and validated enough to predict injuries accurately. Models which will arise from new approaches may be helpful in the future [7, 8].

Component Tests

Component tests are designed to reproduce just the critical part of the whole accident event. A lot of additional knowledge is needed to interpret the results correctly. In a complex context, for example in a pedestrian accident, a component test with fixed test parameters set independently of the geometry of the vehicle's front may be inappropriate in certain constellations. It is not able to represent these accident events detailed enough with all its variations. A number of national and international expert groups are analysing this problem and try to enhance the procedure which nearly inevitably increase the complexity of the test [9].

Figure 2. Typical pedestrian related component test, conducted on behalf of the Technical University of Berlin.

AN ADVANCED ASSESSMENT PROCEDURE

Head impact by far results in the most severe accident consequences representing almost all fatal injuries in a pedestrian-car-collision. Therefore, our approach is focused on it.

Numerical simulations can provide knowledge about the kinematics of the event for each particular car and for diverse impact conditions. The results of the simulation are used to control a free flying head-form test device. The measured acceleration values provide the basis for the assessment of a particular car.

Our assessment procedure therefore combines the following four modules:

- accident analysis
- numerical simulation
- component test
- quantification of pedestrian safety

In order to quantify pedestrian safety and to make sure that the results are comparable for all forms of vehicles on a linear scale, a Vehicle Related Pedestrian Safety index is proposed (VERPS-index). In addition, it provides the opportunity to assess technical measures applied to the car's front to increase pedestrian safety and allows comparison with active safety measures applied to the vehicle (e.g. brake assist system).

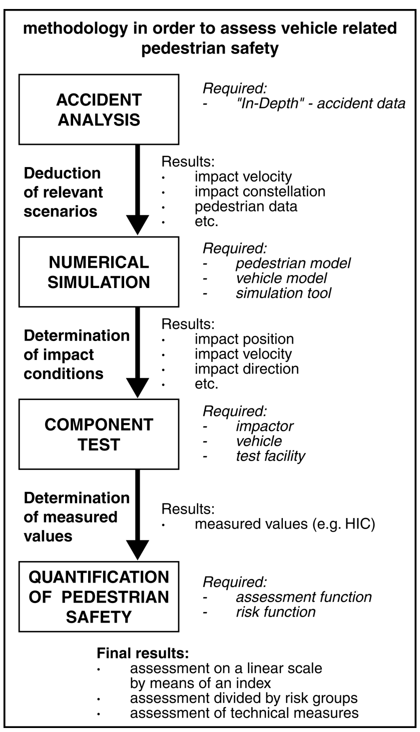

Figure 3. Illustration of the methodology to assess vehicle related pedestrian safety.

Furthermore, the presented method makes it possible to influence the pedestrian friendliness of a product in a very early stage of the vehicle development process by possibly making geometry changes with minor stylistic or functional effects or by triggering the development of additional pedestrian protection systems.

Accident Analysis

A statistical analysis of pedestrian accidents makes sure, that the input parameters used in the numerical simulations are realistic. It provides the basis for all further deductions and needs a regular update. "In-Depth"- data of the Medical University of Hanover are used [10]. The analysis shows that 90 % of all pedestrian accidents occur with a collision speed of less than 45 km/h, covering around 70 % of the severely injured (AIS3+) and around 95 % of the slightly injured pedestrians. In 71 % of all cases the pedestrian hits the front of the car. Thereby, 92 % of the pedestrians were hit laterally from the right or left side. 94 % of these pedestrians were walking or running the moment prior to the collision. The most frequently injured body parts were the lower extremities (35 %) and the head (33 %). Deadly injuries can be attributed exclusively to the head impact.

Numerical Simulation

For the analysis of the kinematics of the head impact on the front of a vehicle a numerical simulation process has been developed. It is based on the multibody simulation tool MADYMO. The pedestrian is represented by the Full Body Pedestrian Model of TNO. The vehicles are modelled using finite elements. The structure of the vehicle's front is represented using a global stiffness.

Validation of the simulation model was done in three ways. At first, calculated longitudinal throwing distances were compared to those, which resulted from carefully analysed real accidents. At second, the kinematics of well documented PMHS-tests and simulation results for the primary impact were compared. Finally, a very precisely documented real accident was used to compare numerical simulation results to the real accident conditions (see Figure 4) [11]. It could be shown that the simulation model is able to represent the primary impact of a pedestrian to the vehicle front very well. Thus, the model can provide reliable kinematical impact conditions for a component test. It is not intended to predict injuries with this simulation model.

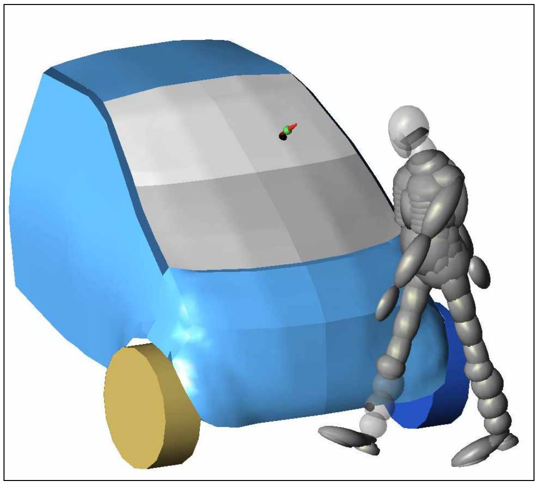

Figure 4. Reconstruction of a real pedestrian-car accident. [11]

For each set of simulations for a VERPS-rating a number of characteristic parameters has to be defined. One group of them describes the impact between car and pedestrian (speed of the car, direction, speed, and size of the pedestrian, location of the first contact between pedestrian and car, angle between pedestrian and car) and is independent of the vehicle. The combination of these parameters results in 32 impact constellations for each analysed vehicle model (see Table 1).

Table 1.

Vehicle specific input parameters.

input parameter	**selected values**	**number of simulations**
pedestrian size	four dummy sizes according to TNO-Human-Model family; (6y-child, 5% female adult, 50% male adult, 95% male adult)	4
walking velocity	1.5 m/s and 3.1 m/s	2
angle between pedestrian and vehicle	90° and 75°	2
initial impact location of the pedestrian	two positions along the vehicle front; central (0.0 m), eccentric (0.4 m)	2
simulations per vehicle		**32**

The other group represents properties of the car (geometry of the vehicle front, braking pitch angle). Additional parameters can be used to include active safety features like brake assistant, pre-crash sensors, etc.

The impact velocity is set to 45 km/h according to results of the accident analysis. With the help of the accident analysis it can be shown, that the four pedestrian sizes used cover 76 % of all involved persons, if a tolerance of ± 0.1 m in body height is accepted.

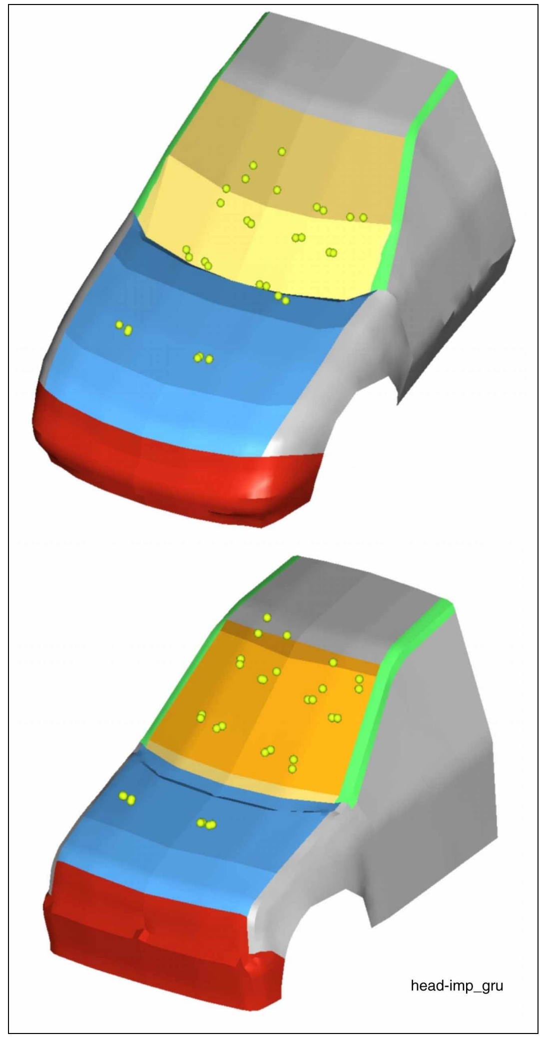

Figure 5. Calculated head impact positions for four pedestrian sizes at v_C = 45 km/h. (above: vehicle F, below: vehicle G).

Figure 5 and Table 2 show the calculated head impact conditions for two different cars (distance to impact position = WAD, impact angle = α, impact velocity = v_c). The calculated values represent the geometry of the analysed vehicles and differ considerably from the European directive [1]. Based on the simulation results also the mass of the appropriate head impactors can be allocated.

Table 2.

Calculated head impact parameters for sample cars F and G.

		pedestrian percentile			
		6y-old child	**5 % female**	**50 % male**	**95 % male**
height	**h [m]**	1.16	1.52	1.74	1.91
F_k=WAD/h	**F [ ]**	1.02	1.08	1.15	1.11
	G [ ]	1.01	1.08	1.14	1.09
WAD	**F [m]**	1.16-1.20	1.58-1.71	1.92-2.09	2.10-2.27
	G [m]	1.16-1.19	1.57-1.70	1.87-2.01	1.97-2.22
α	**F [°]**	52	58.5	55.5	56
	G [°]	51	55.5	43.5	48
v_c	**F [km/h]**	35.4	43.9	49.6	49.9
	G [km/h]	32.3	46.7	48.2	44.4

Table 3 shows calculated head masses of the four pedestrian percentiles and allocates them to the headform masses used in our tests.

Table 3.

Calculated head masses and allocation to existing test headforms. [11]

	h [m]	**calculated head mass** m_c [kg]	**allocated headform mass** m_h [kg]
6y old child	1.16	3.5	3.5 (ACEA)
5 %-female	1.53	4.0	3.5 (ACEA)
50 %-male	1.74	4.8	4.8 (EEVC WG 17)
95 %-male	1.92	5.9	4.8 (EEVC WG 17)

The results of the component tests can be represented by HIC values (Head Injury Criterion), calculated from the measured headform accelerations. They show a typical pattern of potentially dangerous regions at the vehicle front:

- parts of the bonnet with little deformation space beneath
- lateral bonnet edge and transition area between bonnet and wing
- bonnet area directly above the firewall
- lower windscreen frame
- A-pillars
- upper windscreen frame and roof frontal edge

All of these areas are characterized by stiff and hence less deformable vehicle structures. The degree of exposure of a pedestrian to these regions can differ from car to car because of differences in dimensions and styling. A test procedure which stringently dictates meeting of specific test limits will unavoidably produce meaningless ratings in these areas.

Because of different vehicle geometries the potentially dangerous areas for the head impact are affected more or less frequently during a pedestrian impact. Some of these areas might be totally irrelevant for the head impact of a pedestrian (e.g. upper windscreen frame at SUV's). For that reason a weighting of the test results concerning their relevance in pedestrian accidents is necessary.

ASSESSMENT OF VEHICLE RELATED PEDESTRIAN SAFETY

In the following a Vehicle Related Pedestrian Safety Index (VERPS-index) is developed. This index assesses the level of safety which a special vehicle can provide for the head of a pedestrian who is impacted by the front of the car. It allows to assess differences between particular vehicle designs and to compare technical measures applied to the vehicle front. The VERPS-index is the result of the quantification module in the proposed methodology (see Figure 3).

Derivation of the VERPS-index

The VERPS-index for the frontal impact is deduced in three steps from the values M_{ij} measured in the component test:

1. Mapping of M_{ij} to the degree of performance E_{ij} by an evaluation function $B(M_{ij})$.

$$E_{ij} = B\left(M_{ij}\right) \qquad (1).$$

2. Weighting of the degrees of performances E_{ij} with relevance factors $R_{i, WAD}$ and $R_{j, front}$, deduced from accident analysis.

$$R_{i,WAD} \cdot R_{j,front} \cdot E_{ij} \qquad (2).$$

3. Summation of degrees of performance for all subareas of the vehicle front to the VERPS-index.

$$VERPS = \sum_{i=1}^{m}\sum_{j=1}^{n} R_{i,WAD} \cdot R_{j,front} \cdot E_{ij} \qquad (3).$$

To assess the vehicle front it is necessary to divide it in subareas. For each of them M_{ij} is measured (see Figure 6). Thereby, subindex i describes the longitudinal direction of the vehicle front and subindex j the transverse one.

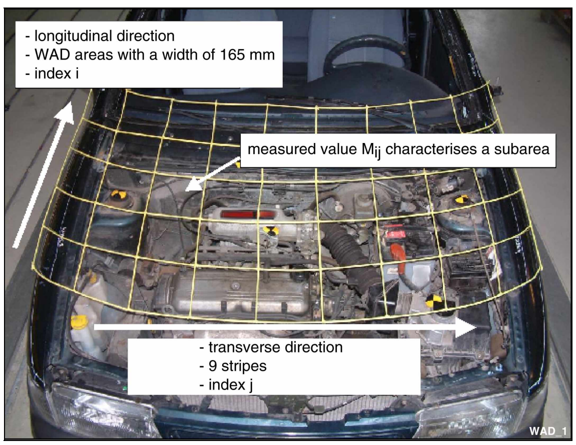

Figure 6. The division of the vehicle front in subareas.

The definition of limit values is an often used possibility to assess measured values. But it allows only a binary assessment. It only distinguishes between good (limit met) and bad (limit exceeded). In order to derive a more refined evaluation an assessment function B can be used to get a functional link between measured values M and the degree of performance E. For the VERPS-index a functional relationship between HIC data and the occurrence of severe head injuries (AIS 3+) is used (Figure 7).

The reduction of a HIC-value by 50 %, e.g. from HIC = 4.000 to HIC = 2.000, improves the degree of performance E only from $E_{HIC=4000} \approx 1$ to $E_{HIC=2000} = 0{,}938$ (see Figure 7). In contrast to that an improvement from HIC = 2.000 to HIC = 1.000 leads to a significant improvement to $E_{HIC=1000} = 0{,}244$; this means a probability for the occurrence of severe head injuries of 24,4 %.

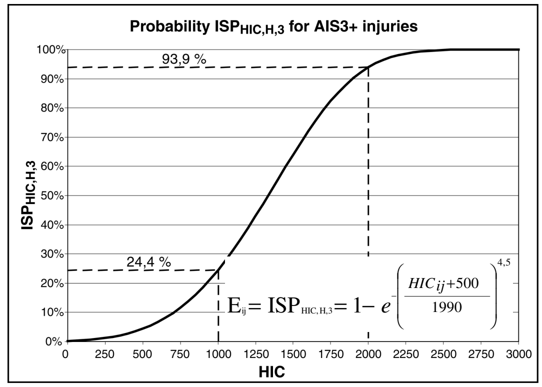

Figure 7. Correlation between measured HIC data and probability of AIS 3+ injuries (ISP – Injury Severity Probability). [based on 12]

In the second step of the calculation of the VERPS-index the degrees of performance E_{ij} are weighted with their relevance in accident events. The importance of a test point obviously depends on the probability of hitting it in real life. In order to deduce the relevance factors, "In-Depth"- accident data of the Medical University of Hanover are used. The relevance factor in the longitudinal direction of the vehicle ($R_{i, WAD}$) describes the correlation between the vehicle specific kinematics factor f_K and the size of the pedestrian. In the transverse direction of the vehicle front an equal distribution for impact locations is assumed. This is supported by accident data.

We calculate the VERPS-index separately for children younger than 12 years and for adults and children older than 12 years. Obviously, other separations are possible. Our choice considers the different requirements of pedestrian safety measures applied to cars for children and adults which result from different body heights. By use of the assessment function $B(M_{ij})$ the VERPS-index can be expressed as follows:

$$VERPS = \frac{1}{9}\sum_{i=1}^{m} R_{i,WAD} \cdot \sum_{j=1}^{9}\left\{1 - e^{-\left(\frac{HIC_{ij}+500}{1990}\right)^{4,5}}\right\} \qquad (4).$$

Figure 8 shows the division of the vehicle front into subareas and their relevance weights for a sample car.

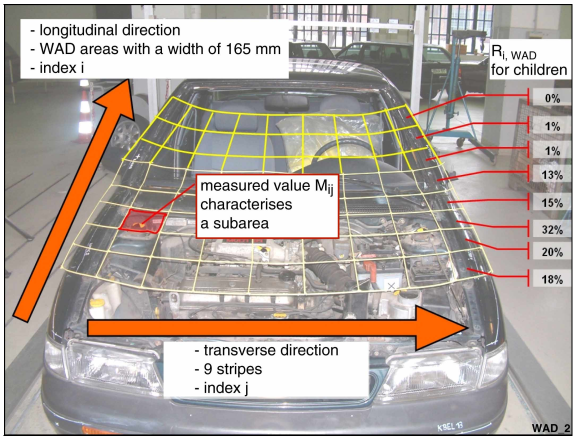

Figure 8. Relevance factors in longitudinal direction ($R_{i,\,WAD}$) for car F.

The VERPS-index can run between (nearly) zero (no risk for AIS 3+ head injuries) and 1 (maximum risk for AIS 3+ head injuries). A car, which has a HIC-value of 1,000 in all subareas of its front, would have a VERPS-index of VERPS = 0.244.

The proposed procedure allows to assess vehicle fronts on a linear scale within the limits of accuracy of the assumptions.

Application of the VERPS-index

The VERPS-index is evaluated for two sample cars. It can clearly be seen, that pedestrian safety has to be assessed separately for children and adults. Pedestrians hit different areas at the vehicle front because of their different body heights. This is the reason why a particular technical measure can positively affect all groups of persons only in exceptional cases.

Two mass-produced vehicles are compared with two modification levels of a possible pedestrian protection system. The first level represents a mechanical system which uplifts the bonnet in the rear area by around 0.1 m in case of a pedestrian impact. In the second level an airbag system is assumed which combines level one measures with an energy absorbing device which covers critical areas of the A-pillars and the lower windscreen frame (see Figure 9). Results can bee seen in Table 4.

Figure 9. Implementation of a system to uplift the bonnet by use of an airbag which also covers the A-pillars and the lower windscreen frame. [9]

Table 4.

Assessment of different cars and pedestrian protection systems by use of the VERPS-index.

		vehicle F	vehicle G
production condition	children	0.54	0.63
	adults	0.63	0.24
uplifting bonnet	children	0.22	0.43
	adults	0.60	0.24
uplifting bonnet combined with an airbag	children	0.08	0.11
	adults	0.25	0.17

For vehicle F the VERPS-index for adults could be reduced from 0.63 to 0.25, for children even from 0.54 to 0.08. The marked reduction of VERPS-index for children shows the great potential of active structural measures, if they are applied properly with respect to pedestrian body height and the vehicle dimensions. Head impact areas, which are mainly hit by adults, can only be protected with the uplifting bonnet and the additional airbag to cover A-pillars and lower windscreen frame (see Table 4).

The VERPS-index of 0.24 for adults of vehicle G in production condition is good compared to vehicle F. This can be traced back to the fact, that all relevant head impact areas for adults are in the windscreen area, which is considered uncritically concerning the HIC results unless the windscreen frame area or the A-pillars are included.

Because of the vehicle front geometry of car G an uplifting bonnet alone can protect only a small group of pedestrians. An additional airbag applied to the lower windscreen frame is able to better protect smaller adults, but the relevant impact areas for taller ones are still not covered. Accordingly the VERPS-index is only reduced from 0.24 to 0.17. For children vehicle G in production condition performs poorer than for adults with an VERPS-index of 0.63, because they quite frequently hit the firewall and the lower windscreen frame with the head. By use of active structural measures the VERPS-performance can be clearly improved. The VERPS-index decreases from 0.63 in series condition to 0.43 for the uplifting bonnet alone and to 0.11 for the uplifting bonnet with the additional airbag.

OUTLOOK

It could be shown that an index can be formulated that allows to assess different vehicles with respect to their pedestrian safety on a linear scale. The VERPS-index allows to compare different vehicles and technical measures like the uplifting hood on the same vehicle concerning their pedestrian protection potential.

We expect, that it will be possible in the near future also to assess active safety measures (e.g. pre crash sensing devices, brake assist systems) on the same scale. The reduction of the collision speed of a vehicle, which can be attained with a certain probability depending on the system layout, can be included in the VERPS-calculation. The reduced collision speed is used as an input parameter for the numerical simulation module. This finally results in an specific VERPS-index for the analysed car.

The comparison of different systems using the VERPS-index also offers the basis for a benefit-cost analysis to identify the most efficient measure in an economic sense [11].

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